A SINGLE-CRYSTAL SILICON VIBRATING RING GYROSCOPE

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ABSTRACT

This paper reports a high-performance vibrating ring gyroscope fabricated in (111) oriented single-crystal silicon (SCS). High-performance microgyroscopes are needed in many applications, including inertial navigation, control, and defense/avionics/space. The ring gyroscope provides a number of advantages, including excellent mode matching, high-resolution, low zero-rate output, and long-term stability. In this paper, a SCS vibrating ring gyroscope with high aspect ratio silicon on glass structure was designed, fabricated and tested. The ring is 2.7mm in diameter and 150μm thick. The gyro has the following measured performance: high Q (12000), good non-linearity (0.02%), large sensitivity (132 mV/°/sec), low output noise (10.4°/hr/√Hz) and high resolution (7.2°/hr). The maximum bias shift is less than ±1°/sec over 10 hours without thermal control.

Key words: gyroscope, inertial, silicon-on-glass

INTRODUCTION

High-performance and low-cost micromachined vibrating gyroscopes have many applications [1-4]. To increase sensitivity, the difference between the resonant frequencies of drive/sense modes should be reduced as much as possible. However, most vibrating gyros require mechanical trimming for tuning, and show strong temperature drift due to mismatching of mode frequencies. The vibrating ring gyroscope (Fig. 1), working at two degenerate flexural modes, has intrinsic mode matching. The first nickel vibrating ring gyroscope was reported in 1994 and had a resolution of 0.5°/sec [4]. A polysilicon high aspect-ratio ring gyroscope with improved performance over Ni gyro has also been proposed [5] recently. But, ring gyroscopes have themselves drawbacks: small vibrating mass and low sense capacitance. To further improve the performance of a ring gyro to provide a resolution of ~1-10°/hour, the vibrating mass and sense capacitance have to be increased. (111)-oriented single-crystal silicon (SCS) ring with high aspect ratio, supported by glass substrate, provides a possible device to achieve high performance.

The vibrating ring gyro consists of a ring, 8 support springs, and drive, sense and control electrodes (Fig.1). The ring is electrostatically driven into the elliptically-shaped primary flexural mode with a fixed amplitude. When the device is subjected to rotation, Coriolis force causes energy to be transferred from the primary mode to the secondary flexural mode, which is degenerate with the drive mode and located 45° apart from it, causing a build-up of oscillation amplitude proportional to the rotation rate. This build-up is capacitively monitored. In order to ensure that the SCS ring gyro operates properly, (111) silicon is used because it has uniform and homogeneous material properties such as Young's modulus over the (111) surface [6]. This is critical for the ring gyro to be able to obtain matching degenerate flexural sense and drive modes that track over temperature. Silicon deep RIE is used to provide high aspect ratio structures to increase the sense capacitance and vibrating mass. The silicon is bonded to a support glass substrate (silicon-on-glass, SOG), which minimizes parasitic capacitance to improve sensitivity. In this paper, we report our recent research on SCS vibrating ring gyroscopes.
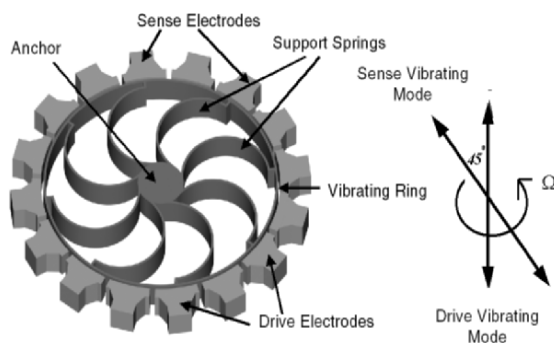

Figure1: Structure and operation of vibrating ring gyroscope

DESIGN

The resonant frequency of SCS gyro was designed to be larger than 20 kHz to eliminate environmental noise. The vibrating ring has a diameter of 2.7mm, is

50μm wide and 150μm thick. The support springs, which are different from semi-circle springs used before [4, 5], are designed as meander-shaped and optimized by FEM. Theoretical calculation shows that this particular design provides better mode matching and facilitates tuning. The anchor, which is fixed on the glass substrate and connects with support springs, is in the center of the ring with a diameter of 300 μm. The resonant frequency of the SCS gyro is 28.5 kHz simulated by ANSYS. The total die size is 4mm x 4mm.
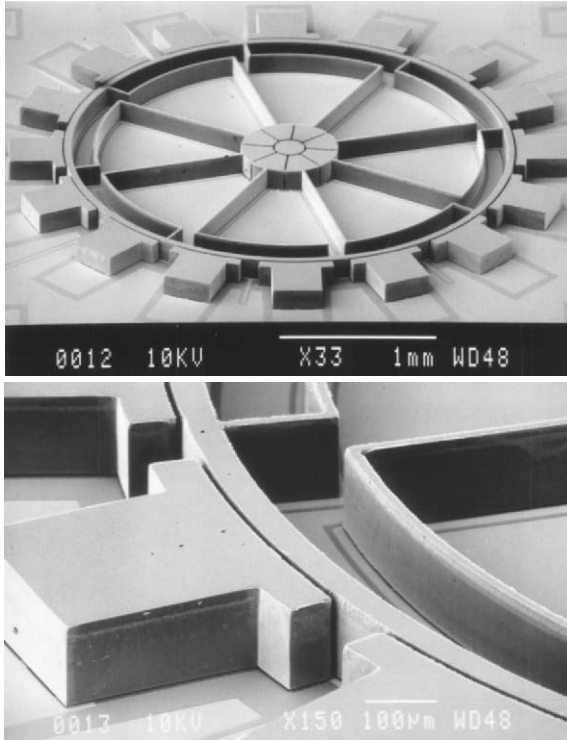

Figure 2: SEM picture of SCS vibrating ring gyroscope (above). Close up view of ring structure, sense electrode and 8 μm sense gap (below).

FABRICATION

A (111) silicon wafer (480μm thick) with low resistivity (0.002 Ω-cm) is first patterned and etched using DRIE to a depth of ~150μm to form the ring gyro and its sense/drive electrodes. The wafer is then bonded face down to a #7740 glass wafer, which has formed in it a recess under the moving ring, and also supports metal interconnects for the gyro. The silicon wafer is then etched from the backside in RIE until the gyroscope is released. The fabrication process is simple, requires only low-temperature steps, and can produce very large thickness and relatively small gaps. Figure 2 shows an SEM of the SCS ring gyro and a close up view of one of the sense/drive

electrodes and the ring. After fabrication, the ring is 152μm thick and 46μm wide, which is a little bit different from the design values due to fabrication variations. This high aspect ratio single crystal silicon ring provides a large vibrating mass and reduces thermal noise.
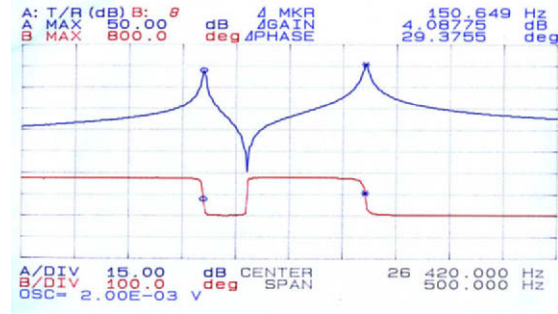
(a) Before balancing
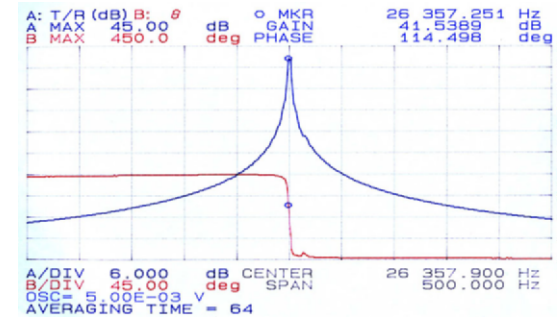
(b) After balancing

Figure 3: Frequency spectrums of drive and sense modes in SCS ring gyro before and after balancing. Balancing voltage is ~60V. Q after balancing is 12000.

FREQUENCY RESPONSE AND ELECTRONIC TUNING

The measured resonant frequencies of flexural modes in SCS ring gyro are shown in Figure 3 (a), and are a little bit lower than their calculated values (28.5 kHz) due to process variations. In practice, the two degenerate flexural modes are not matched and the frequency split between them can be as large as 150Hz (0.58%). Electric tuning is an effective method to bring the two flexural modes together. This is important in all vibrating gyroscopes to maximize their sensitivities. Careful design of support springs is necessary for SCS ring gyros to make sure their two flexural modes can be matched. Figure 3 shows the resonant frequencies of the two flexural modes of the gyro before and after balancing. In the current SCS gyro design, a large tuning voltage (~60V) is applied on the control electrodes, which are located around the ring, to match the two modes. The large tuning

voltage is due to the large sense gap. Modifying the fabrication process to decrease the sense gap, for example by filling the gap with doped polysilicon, could further reduce the balancing voltage. The quality factor after balancing is larger than 10000. The SCS ring gyro provides a large mass, large sense capacitance, high Q and high sensitivity, all of which are critical to improve the gyro performance to the level needed in tactical and inertial applications. Table 1 summarizes the characteristics of fabricated SCS vibrating ring gyroscope.

Table 1: Characteristics of the fabricated single crystal silicon vibrating ring gyroscope

Parameters	Designed	Measured
Ring diameter (mm)	2.7	2.7
Ring thickness (µm)	50	47
Ring height (µm)	150	152
Resonant freq. (kHz)	28.53	26.36
General mass (mg)	0.121	0.116 (estimated)
Sense gap (µm)	6	8
Polarization voltage (V)	50	50
Balancing voltage (V)	N/A	60
Driving amplitude (µm)	0.3	0.123 (driving volt. 70.5mV)
Quality factor	10000	12000
Mech. Sensitivity (mV/V/°/sec)	2.12 1.38 (after fabrication)	1.04

READOUT CIRCUITRY, PACKAGE AND TEST

Figure 4 shows the gyro housed in a metal DIP package with a hybrid readout buffer. The buffer is a simple source-follower stage designed by using a low-noise JEFT with a bootstrapped input to minimize parasitic capacitance. The measured equivalent input noise voltage of the interface circuitry is less than 30nV/$\sqrt{Hz}$ at 30Hz. Additional gain of 65dB is provided after the buffer stage. The control electronics for the ring gyroscope includes four loops, and is built on a breadboard [4]. A single axis automatic positioning and rate table with a resolution of 0.36°/hour made by Ideal Aerosmith Inc (Model 1601-2) is used to test the gyro rate output. The frequency spectrum of the gyro is measured and is used to balance the two flexural modes. The gyro's output noise spectrum is measured using a HP3561 dynamic signal analyzer.
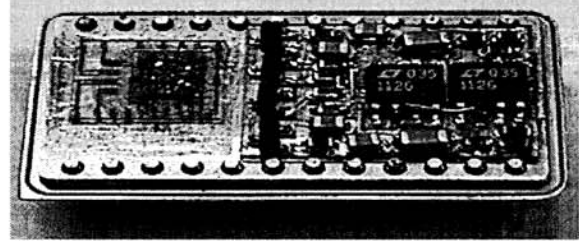

Figure 4: Hybrid packaged gyroscope and interface chip.

PERFORMANCE MEASUREMENTS

The device is operated in open-loop mode for rate testing. At first, electrostatic balancing of the device is performed. Figure 5 shows the measured rate output of the gyroscope over a range of ±15°/sec. The gyro has a sensitivity of 132mV/°/sec, which is much higher than the Ni gyro of 10mV/°/sec [4] and polysilicon ring gyro 0.2mV/°/sec [5]. The measured non-linearity 0.02% in the ±15°/sec measurement range, and it can be further improved by operating the gyro in force-to-rebalance mode. The DC rate resolution of the SCS ring gyro is approximately 0.02°/sec in 10Hz bandwidth, which is limited by quadradure error. The sinusoidal output rate response of the gyro to an input rotation rate of 1°/sec at 2Hz is shown in Figure 6.
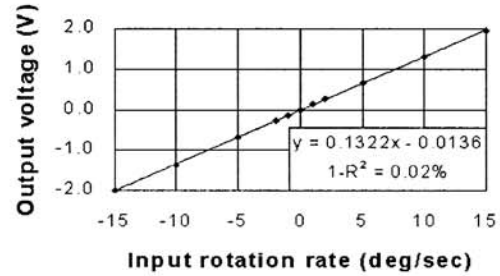

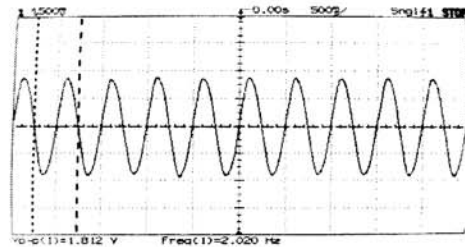Figure 5: Measured rate results from the SCS ring gyroscope, with a sensitivity of 132 mV/°/sec.

Figure 6: Analog output voltage when applied input rate of 1sin(4πt)°/sec.

The resolution of the single crystal silicon ring gyroscope is determined by analyzing the noise spectrum, which is shown in Figure 7. In this figure, the input rate is 1°/sec at 10Hz. The gyro output here is –31.45dBV while the noise floor is –76.4dBV. The noise equivalent resolution of the SCS ring gyro system is 10.4°/hour/√Hz. A resolved input rate signal of 7.2°/hr at 2Hz is shown in Figure 8 with a measurement integration time of 100sec.
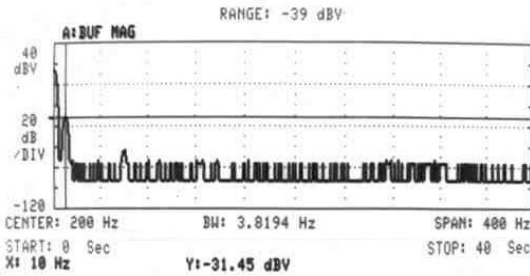

Figure 7: The gyro noise spectrum analysis while the input sinusoidal rate is 1°/sec at 10Hz. The estimated gyro resolution is 10.4°/hr/√Hz.
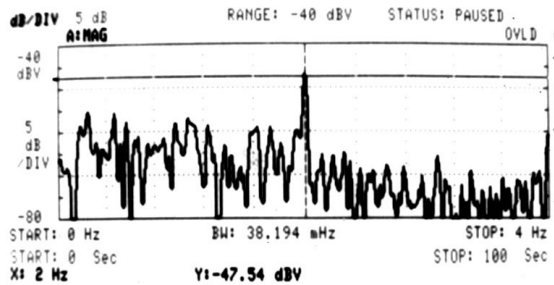

Figure 8: Resolved sinusoidal signal peak of 7.2°/hr at 2Hz with 100 seconds measurement integration time.

The bias stability of the SCS vibrating ring gyroscope is tested in 10Hz bandwidth without temperature control, and is shown in Figure 9. The maximum bias shift after 10 hours is less than ±1°/sec. The bias stability can be further improved by temperature compensation.
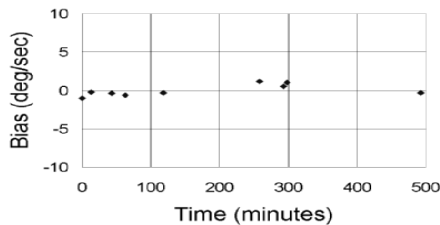

Figure 9: Bias stability without thermal control

CONCLUTIONS

A single-crystal silicon vibrating ring gyroscope was designed, fabricated and measured. Initial testing shows that it has high Q, high sensitivity, low output noise and high resolution. Some performance specifications are list in Table 2. With thermal control and temperature compensation the gyroscope should be capable of providing a resolution of 1°/hr.

ACKNOWLEDGMENTS

Table 2: Performance specifications of the single-crystal silicon vibrating ring gyroscope

	Designed	Measured
Sensitivity (mV/°/sec) (at driving volt. of 70.5mV)	173	132
Dynamic range (°/sec)	>±50	>±50
Non-linearity		<0.02%
Equiv. input volt. noise of readout ckt. (nV/ √Hz)	18	30
Resolution (including Brownian and electronic noise) (°/hr/√Hz)	9.74	10.4
Min. det. signal [°/hr]		<7.2

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